Investigation of the Flow in the Diffuser Section of the NASA Lewis Icing Research Tunnel

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The flow in the diffuser section of the Icing Research Wind Tunnel at NASA Lewis Research Center is investigated using both tunnel calibration measurements and numerical simulation techniques. Local pressure and temperature measurements are made to establish velocity and temperature profiles in the diffuser of the tunnel. These profiles are compared with similar measurements made prior to renovating the equipment which generates the tunnel's icing cloud. This comparison indicates the manner in which this change affected the flow. The measured data were also compared with a numerical simulation of the flow to help understand how such changes may favorably alter the tunnel flow.

NOMENCLATURE

a	= speed of sound
g	= acceleration due to gravity
Ma	= Mach number
P_s	= absolute static pressure
P_t	= absolute total pressure
ΔP_s	= local static pressure-reference total pressure difference
ΔP_t	= local total pressure-reference total pressure difference
R	= universal gas constant for air
T_s	= absolute static temperature
T_t	= absolute total temperature
V_{tc}	= true compressible velocity
V_{ti}	= true incompressible velocity
γ	= ratio of specific heats for air

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INTRODUCTION

Wind tunnel diffusers have often been used as a second, lower speed, test section for models which were too large to be effectively tested in the tunnel test section. However, wind tunnel diffusers can have airflow characteristics which are undesirable for accurate testing such as: large wall boundary layers, high levels of turbulence, a non-uniform velocity profile, and an increased probability of flow separation along the diffuser walls. Most of these undesirable characteristics are the result of the adverse pressure gradient inherently present in a diffuser. A number of different methods have been used to minimize or reduce these effects. Among them are vortex generators, windmills, splitter plates, and boundary layer control slots which employ blowing or suction to alter the boundary layer.

Due to the great demand for testing time in the NASA Lewis Research Center's (LeRC) Icing Research Tunnel (IRT), there has been much interest expressed in using the diffuser section of this tunnel as a test section provided that the flow characteristics, both for the air and the water droplets, could be altered.

In order to more effectively design a method to favorably alter the flow, an investigation of the IRT diffuser flow characteristics was undertaken. This investigation includes both local velocity and temperature measurements in the tunnel and computational modelling of the flow.

Background

Measurements of the IRT diffuser flow made in mid-1960's by LeRC's Diedrich[1], later corroborated by Cubbison[2] in a more general tunnel performance study, revealed that highly nonuniform velocity profiles such as those shown in Figs. 1 and 2 occur at all tunnel airspeeds. These profiles proved to be unacceptable for many aerodynamically dependent icing tests. The parabolic shape of the profiles is expected in a diffuser where the adverse pressure gradient and decelerating flow promote an increase in the boundary layer thickness. The asymmetry of the velocity profile about the center of the symmetrical diffuser in both the horizontal and vertical planes supports the argument that flow separation occurs at the walls, although no flow visualization techniques have conclusively verified this assertion.
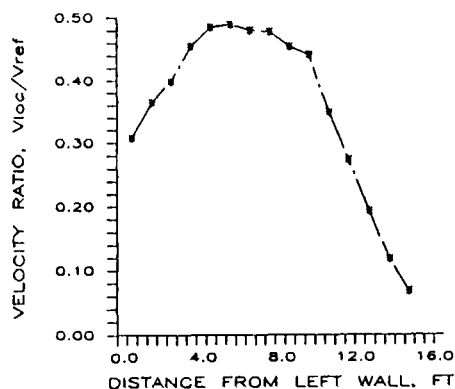

Fig. 1 Early Measurement of Horizontal Velocity Profile in IRT Diffuser

Some previous diffuser studies, documented in the literature, do lend some insight to this phenomena. Truckenbrodt in Schlichting's "Boundary Layer Theory"[3] acknowledges the existence of asymetric flow under certain conditions noting that:

For semi-angles up to 4° in a divergent channel the velocity profile is symmetrical over the width of the channel and shows no features associated with separation. On increasing the angle

beyond 4° the shape of the velocity profile undergoes a fundamental change. The velocity profiles for channels with 5°, 6°, and 8° of divergence ... cease to be symmetrical. With 5° angle of divergence ... no back flow can yet be discerned, but separation is about to begin on one of the channel walls. In addition the flow becomes unstable so that, depending on fortuitous disturbances, the stream adheres alternately to one or the other wall of the channel. Such an instability is characteristic of incipient separation.

Truckenbrodt goes on to state that at higher angles of divergence, a region of reverse flow is observed and the oscillation frequency of the stream increases. The IRT diffuser flow measurements refered to above did not reflect any such flow stream oscillation although flow visualization techniques do indicate some evidence of incipient separation.
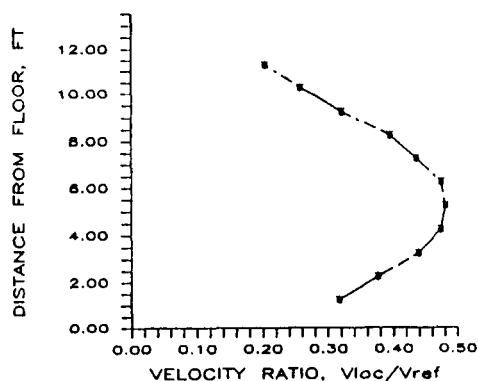

Fig. 2 Early Measurement of Vertical Profile in IRT Diffuser

In a separate study, Reid[4] of Stanford University found that a continuous, or nonfluctuating, asymmetric flow did exist under certain conditions. These conditions were wherever the ratio q_2/q_{2i} dropped below 1.0 in the diffuser regardless of the angle of divergence. The ratio q_2/q_{2i} is the ratio of the actual dynamic pressure at the diffuser centerline to the dynamic pressure which would exist at that same location in the diffuser if the flow were inviscid. Since q_2 differs from q_{2i} along the same streamline only when the streamline crosses any part of the boundary layer, Reid surmized that the asymmetric velocity profiles occured only where the boundary layers encompassed the entire flow across the diffuser.

However, these observations were made in two-dimensional diffusers. The IRT diffuser is three dimensional having rectangular inlet dimensions of
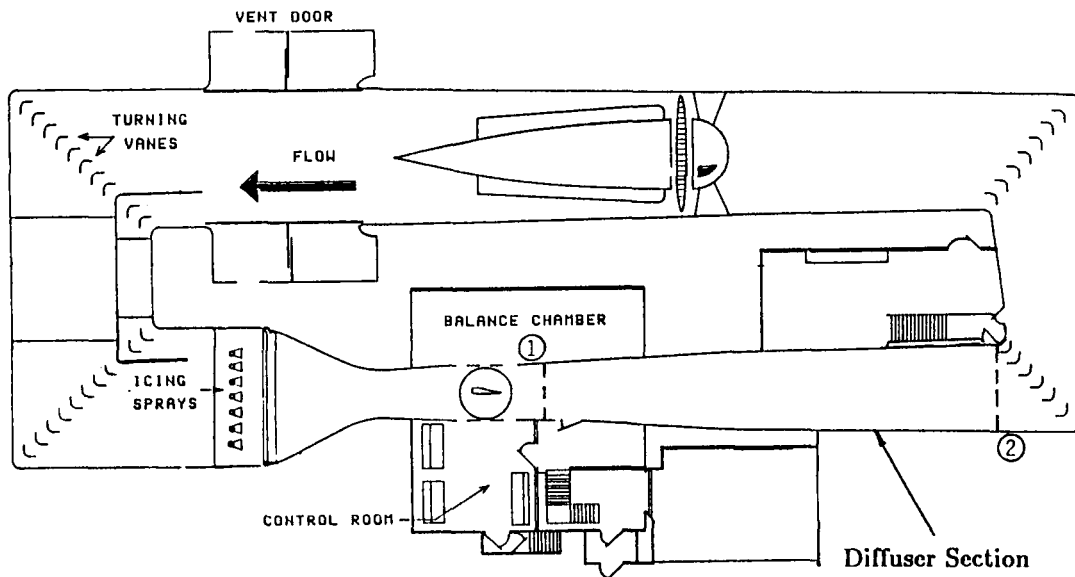
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Fig. 3 Icing Research Wind Tunnel

Measurement Locations: ① Diffuser Entrance, ② Diffuser Exit

6.0 feet by 9.0 feet, outlet dimensions of 13.469 feet by 16.469 feet, and four straight walls diverging at 2.5° semi-angles in both the horizontal and vertical planes. Unfortunately, very little information exists about three-dimensional diffusers.

FACILITY AND PROCEDURE

The IRT is a closed loop wind tunnel designed for test section airspeeds of up to 300 mph. A large refrigeration system allows the tunnel total temperature to be independently set as low as -20 °F. Air flows from the settling chamber through a 14.13:1.0 contraction ratio into the test section which is 20 feet long and has a cross section of 6 feet by 9 feet. The diffuser is 81.5 feet long and has an expansion ratio of 4.11:1.0.

Figure 3 shows where measurements of the flow were made for this study. At each location, local total temperatures and static and total pressures were measured using instrumentation rakes as shown in Figs. 4 and 5. These rakes were designed to minimize their effect on the flow and on the measurements themselves.[5,6]

The pressures from the instrumentation rakes were measured by individual transducers on an Electro-Scan Pressure System (ESP). This system employs oscillating quartz crystals and is a secondary standard tracable to the National Bureau of Standards. Each transducer is of the differential type and was referenced to the tunnel total pressure

which was measured by the facility Pitot-static tube. Both 1.0 psid (pounds per sq. in., differential) and 5.0 psid transducers were used in the tests. The 1.0 psid transducers have an accuracy of ±0.003 psi while the 5.0 psid transducers have an accuracy of ±0.007 psi. The tunnel total pressure was measured using a 15 psia ESP transducer.
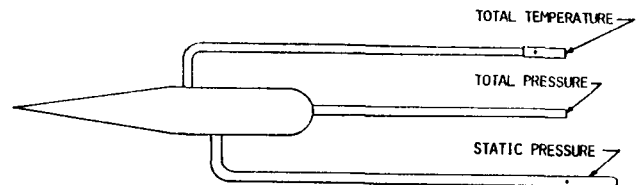

Fig. 4 Side View of Instrumentation Rake

The local total temperatures were measured using aspirated, copper-constantan thermocouples which were referenced to a floating point thermocouple junction box. The temperature of the floating point junction box was measured by a platinum resistance thermometer. For routine tunnel testing, the total temperature is monitored by eleven copper-constantan thermocouples which are mounted on the turning vanes located

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downstream of the refrigeration system and upstream of the contraction section of the tunnel. These thermocouples are also referenced to a floating point thermocouple junction block. The average of the temperatures read by these thermocouples was used to set the tunnel operating temperature. The overall accuracy of each individual temperature measurement is ±0.75°F.

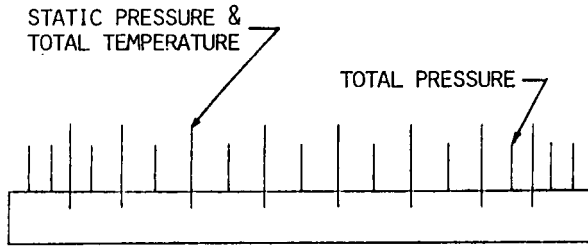STATIC PRESSURE & TOTAL TEMPERATURE

TOTAL PRESSURE

Fig. 5 Top View of Instrumentation Rake

Data recording was provided by a mini-computer based (DEC PDP/1170) system known as Escort II. This system makes a complete scan of the data in approximately 1.5 seconds. Five such scans were averaged to constitute one recorded reading of the data. Additionally, the ESP system makes twenty scans of all pressure transducers and averages the scans of each one to determine the pressure for each port. Thus, each Escort II reading represents the average of 100 samples for each pressure and five samples for each temperature.

An error analysis[7] was conducted prior to flow measurement work in order to determine the most accurate method to calculate the flow parameters from the data. The results of the analysis show that the incompressible calculation of velocity Eq. (1) is the least sensitive to measurement errors. An expression for the velocity in units of ft/s is:

$$V_{ti} = 58.5915 \left[\frac{\Delta P_t - \Delta P_s}{P_s} T_s \right]^{1/2} \qquad (1)$$

However, at speeds in the 150 mph range and higher, the incompressible value differs from the true compressible velocity value, which may be computed by employing Eqs. (2)-(5), by as much or more than the maximum uncertainty in the true compressible velocity calculation.

$$Ma = \left[5 \left\{ \left(\frac{P_t}{P_s} \right)^{2/7} - 1.0 \right\} \right]^{1/2} \qquad (2)$$

$$T_s = T_t \left[1.0 + \frac{\gamma - 1.0}{2.0} Ma^2 \right]^{-1} \qquad (3)$$

$$a = \left(\gamma g R T_s \right)^{1/2} \qquad (4)$$

$$V_{tc} = Ma * a \qquad (5)$$

As a result, the true compressible velocity calculations will be used in the discussion of the results of the measurements at the diffuser section entrance where the velocity is usually in the higher range, while the incompressible velocity calculation will be used in the discussion of the results of the measurements at the diffuser exit where the velocity never exceded 100 mph.

The measurements and calculations were nominalized to minimize the effects of small variations in tunnel conditions from test run to test run. Local pressure measurements were nominalized by the facility Pitot-static tube pressure measurements; the local temperatures were nominalized by the average of the eleven facility total temperatures; and the local velocity calculations were nominalized by the velocity calculated from the facility Pitot-static tube and the average facility temperature.

Measurements were taken at six tunnel airspeeds: 50, 100, 150, 200, 250, and 300 mph at an average tunnel temperature of 0°F at the diffuser entrance. In an earlier study[7], it was found that variation in the average tunnel operating temperature had no noticable effect on the flow characteristics. The instrumentation rakes used in the diffuser section exit were much longer than the rakes used in the diffuser entrance and exhibited

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excessive vibration at the higher speeds; therefore, measurements were taken at only five tunnel airspeeds: 50, 100, 150, 200, and 228 mph (as measured by the facility Pitot-static tube).

NUMERICAL SIMULATION

In order to help gain a better insight to the IRT diffuser flow characteristics and to aid in designing methods to favorably alter these characteristics, part of this study has involved numerically modelling the diffuser flow with a three-dimensional, turbulent, compressible, subsonic flow code designated PEPSIG. This code uses a forward marching procedure to solve a parabolized form of the Navier-Stokes equations. By assuming: 1) that second derivatives in the primary flow direction are negligible, and 2) that the pressure in the streamwise direction momentum equation can be represented by the sum of a known three-dimensional pressure field and a one-dimensional correction computed as part of the marching procedure to account for viscous blockage, a set of equations were derived from the full Navier-Stokes relations which are solved by a single sweep spatial marching procedure in the primary flow direction. These assumptions allow the code to reach a solution using much less cpu time than complete Navier-Stokes codes require and have provided accurate results in a number of cases[8,9,10,11]. On the other hand, these same assumptions prohibit the code from modelling separated or reversed flows as may occur in the presence of an adverse pressure gradient. If such an event is encountered, the code uses a so-called FLARE approximation[12] which replaces negative velocity values with very small positive values and then continues with the calculations. However, if a large area of separated flow is found, the code is unable to procede further and the run is terminated.

The analysis can be applied to duct and diffuser geometries having both curved and straight centerlines and superelliptic cross sections. The cross sections of both the IRT test and diffuser sections are rectangular which at present cannot be handled by the PEPSIG code; therefore, the most highly superelliptic cross section was used in the simulation.

The PEPSIG code is run in two stages. The first stage generates the three-dimensional pressure field for the given input geometry. This is accomplished using a potential flow solver which is elliptic in nature and which has a limited finite

element mesh size. The portion of the IRT which can be modeled by PEPSIG is limited by this constraint to the last 10 feet of the test section and the 81.5 feet of the diffuser. Figure 6 shows the mesh used by PEPSIG to model the IRT flow. One half geometry symmetry was assumed. In the second stage of the calculations a viscous solution for the flow is generated. Mach and Reynolds numbers were calculated for the IRT flow conditions based on a unit dimension, a given velocity, and the properties of air at 0°F and 1 atmosphere.
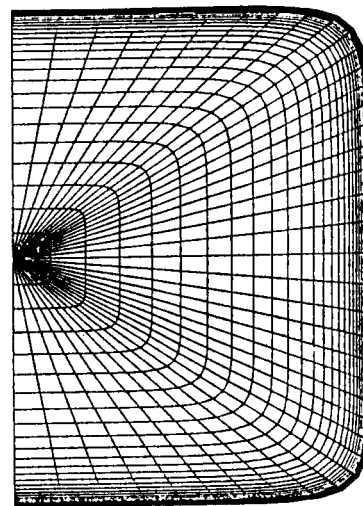

Fig. 6   Cross-Section of a Mesh Used by PEPSIG to Simulate IRT Diffuser Flow

As an extension to the numerical investigation, a code which is based upon the complete Navier-Stokes equations, written in strong conservation form, is currently being used to model the IRT diffuser flow. This code, designated PARC[13], uses an implicit method to solve a set of finite difference equations which are generated by central-differencing the Navier-Stokes equations on a regular grid. It calculates the flow characteristics based on a specified boundary geometry and the corresponding flow conditions on these boundaries. The code permits a wide range of boundary geometries to be specified. Figures 7 and 8 show the mesh currently being used with the PARC code to model the IRT flow.
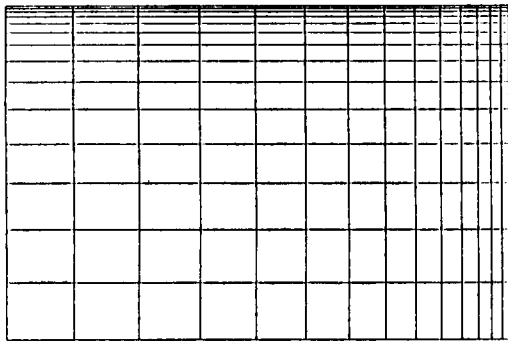

Fig. 7   Top View of Mesh Used With PARC

Fig. 8 Cross-Section of Mesh Used With PARC

A one quarter geometry symmetry is being assumed in this instance.

RESULTS AND DISCUSSION

Results of the flow measurements will be presented first, followed by a comparison of this data with earlier measurements. Finally, the flow characteristics predicted by PEPSIG will be compared with the measured flow.

At each of the tunnel airspeeds, three readings were recorded to verify the repeatability of the data as shown in Fig. 9. The excellent consistency of the data is typical of all the data recorded at the various airspeeds. Also, Fig. 9 depicts the format in which velocity, temperature, or pressure profiles will be displayed. For horizontal profiles, as in this case, the location of each local measurement is plotted along the x-axis as a function of the horizontal distance from the left wall of the tunnel (facing downstream). The nominalized value of each local measurement is then plotted along the y-axis.

Fig. 9 Data Repeatability

For a vertical profile, the axes will be will be reversed. In other words, the location of the local measurement is plotted along the y-axis as a function of the vertical distance from the floor of the tunnel, while the nominalized value of each local measurement is plotted along the x-axis. Additionally, the measurements made in the diffuser entrance included instrumentation rakes which were mounted in each corner as shown in Fig. 10. The measured values for these rakes are plotted along with the vertical profiles and each local measurement location is, again, its vertical location from the floor of the tunnel.
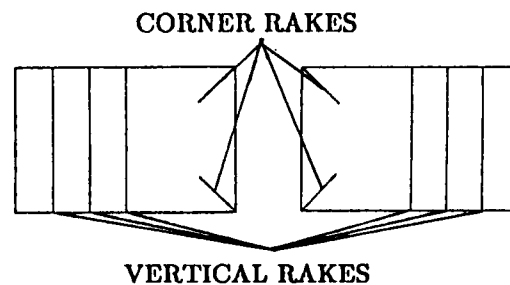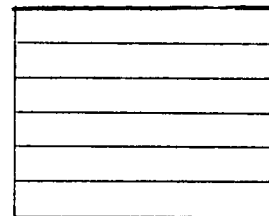
CORNER RAKES

VERTICAL RAKES

Fig. 10 Two Rake Configurations in Diffuser Entrance

Figure 11 shows the five vertical positions of the horizontal rake used in the diffuser exit.

HORIZONTAL RAKES

Fig. 11 Five Rake Positions in Diffuser Exit

Figures 12 and 13 show typical vertical velocity profiles at the diffuser entrance at tunnel airspeeds of 150 and 300 mph, respectively. The profiles in Fig. 12 are from data recorded when the vertical rakes were installed in the left half of the tunnel with the corner rakes in the right-hand corners. Figure 13 shows profiles recorded when the vertical rakes were installed in the right-hand half of the tunnel with the corner rakes in the left corners. These figures demonstrate that the velocity profiles are primarily flat in both the vertical and horizontal directions across the diffuser entrance.
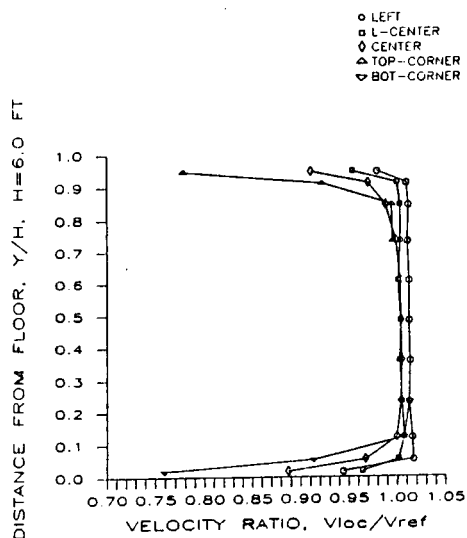
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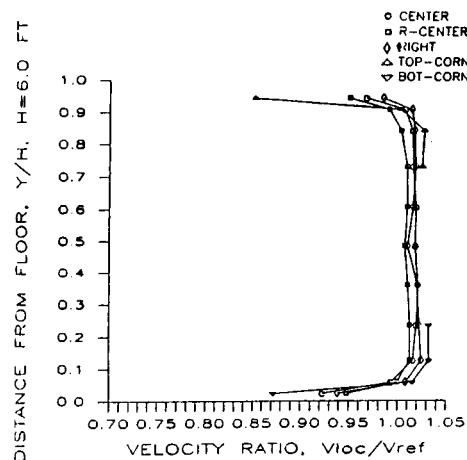Fig. 12 Vertical Velocity Profiles at Diffuser Entrance, Vertical Rakes at Left Side

Fig. 13 Vertical Velocity Profiles at Diffuser Entrance, Vertical Rakes at Right Side
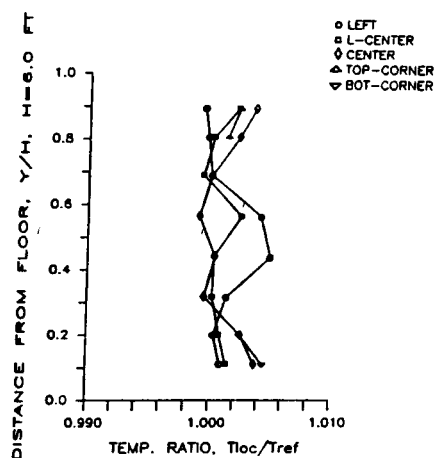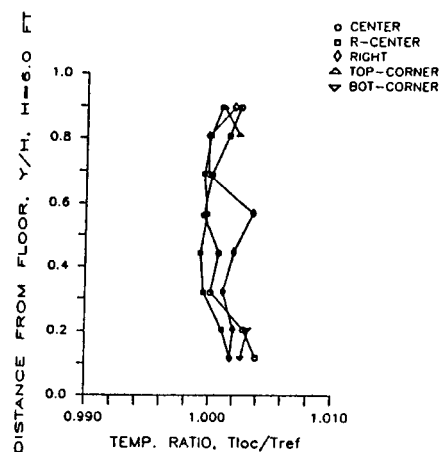

Fig. 14 Temperature Profiles at Diffuser Entrance, Vertical Rakes at Left Side

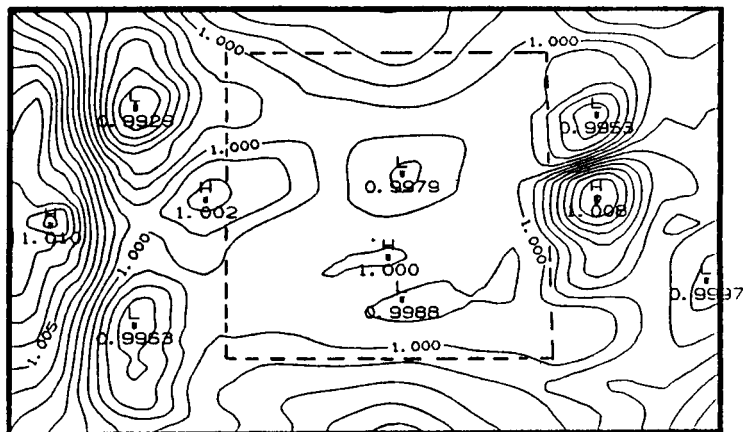Fig. 15 Temperature Profiles at Diffuser Entrance, Vertical Rakes at Right Side

The area of lower velocity flow located near the right-hand wall of the tunnel and about midway between floor and ceiling is a disturbance generated by the facility Pitot-static tube which is mounted on the right-hand wall of the test section, directly upstream of this area.

Local total temperature profiles at the diffuser entrance are shown in Figs. 14 and 15. The average tunnel reference temperature was set to 0°F. Each 0.002 increment in the temperature ratio is equivalent to approximately 1°F.

Figure 16 shows a contour plot of these same local total temperatures at the diffuser entrance. The figure indicates that, generally, the regions of the flow near the left wall is warmer and the effect of the facility Pitot-static tube (which is steam heated to prevent icing) is translated

Fig. 16 Temperature Contours at Diffuser Entrance, 150 mph

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downstream. It is important to note that while temperature variations have little effect on the local velocities in the flow, many icing phenomena are very temperature dependent and a large variation in temperature across the tunnel can adversely influence icing tests more so than a variation in local velocities. If a ±1°F temperature variation restriction is placed on an icing test at this speed, the test area is shrunk to that indicated by the dashed rectangle.

Typical velocity profiles as measured in the diffuser exit are shown in Figs. 17 and 18. The profiles are, as expected, generally parabolic in shape, however, the double parabolas seen in the horizontal profiles are not expected. This trend is least obvious at the horizontal centerline and becomes more exaggerated as the flow is traversed both toward the ceiling and toward the floor of the tunnel. The vertical velocity profiles have only five points per profile and are much less well defined, however, they do suggest nonuniform profiles.

This characteristic can be seen in both velocity contour plots (Figs. 19 and 20) and is more pronounced in the high speed case. These contour plots are somewhat skewed in the vertical direction because measurements were made with only a horizontal rake installed in five different vertical locations approximately 27 inches apart and 27 inches from both the floor and ceiling. It is

Fig. 18 Vertical Velocity Profiles at Diffuser Exit

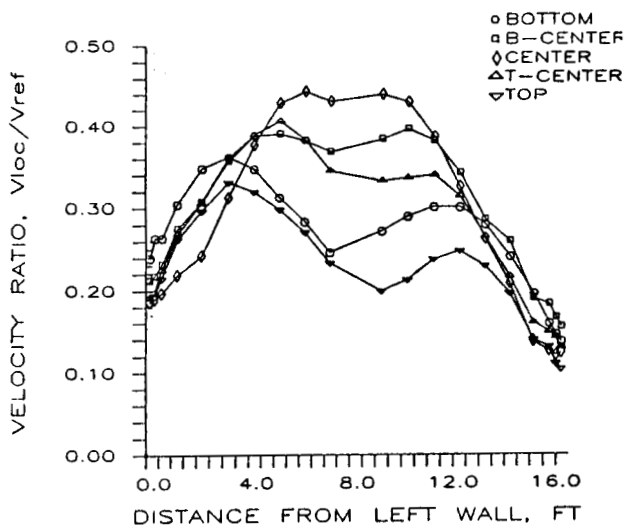Fig. 19 Velocity Contours at Diffuser Exit, 150 mph

Fig. 17 Horizontal Velocity Profiles at Diffuser Exit

anticipated that the more nonuniform flow, as shown near each wall, would be seen near both the ceiling and floor if a vertical rake had also been used to measure the flow.
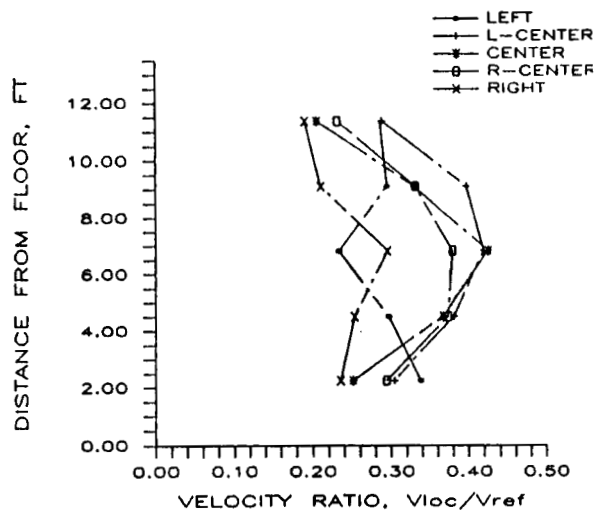

Fig. 20 Velocity Contours at Diffuser Exit, 200 mph
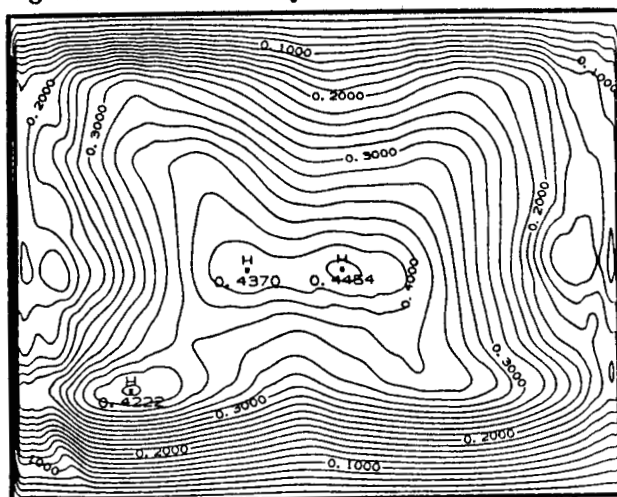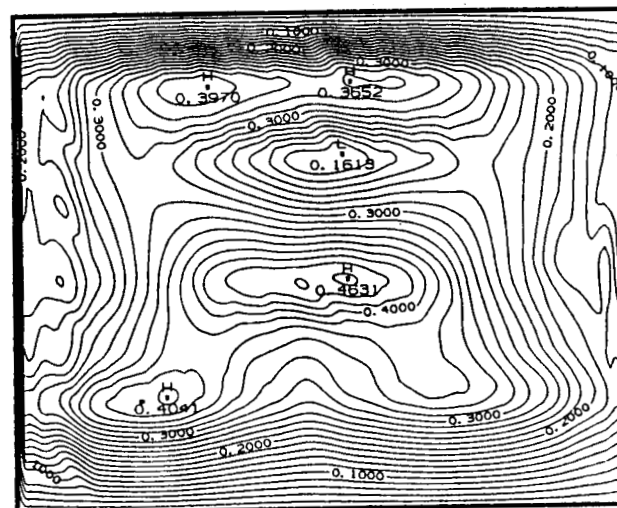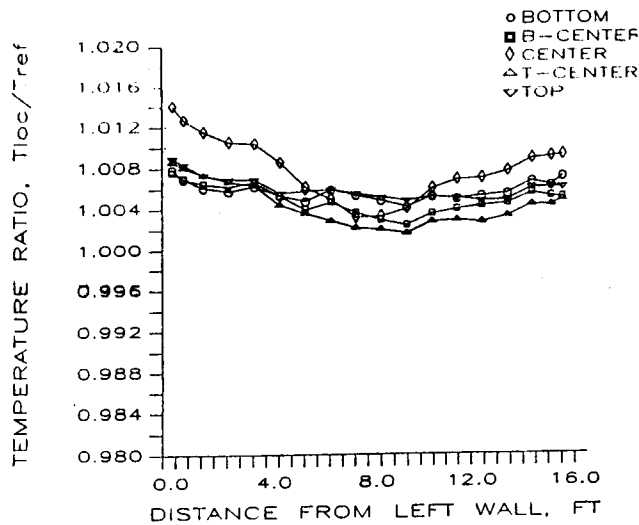
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Fig. 21 Temperature Profiles at Diffuser Exit, 150 mph

Temperature profiles at the five horizontal locations in the diffuser exit are shown in Fig. 21. With the exception of a slightly warmer area near the left wall midway between the ceiling and floor, the entire diffuser is within a temperature range of ±1.5°F at this speed which is very good when compared to the temparture variation in the test section. A similar result is apparent in the in temperature contour plot for the diffuser exit as shown in Fig. 22. This observation is an indication of the high degree of mixing which occurs in a turbulent diffuser.
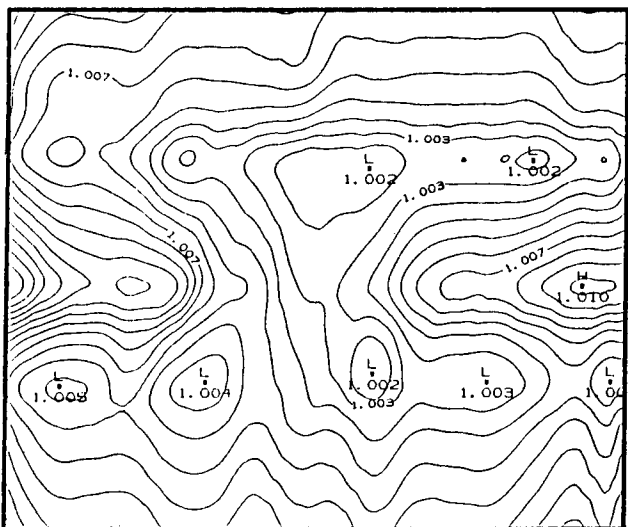

Fig. 22 Temperature Contours at Diffuser Exit, 150 mph

Figure 23 is a comparison of two horizontal velocity profiles located at the centerline of the

diffuser exit at the same speed. One profile was measured recently for this investigation while the other was measured approximately four years ago prior to a renovation of the control systems and
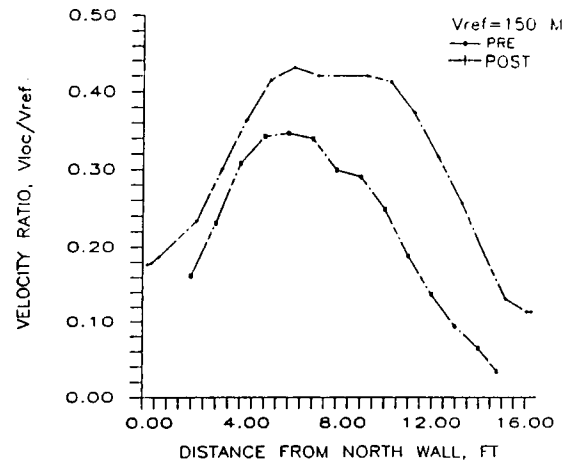

Fig. 23 Comparison of Horizontal Velocity Profiles at Diffuser Exit Before and After Equip. Change

spray bars for the IRT. A number of flow obstructions were removed from the right-hand wall of the settling chamber of the tunnel. This modification appears to have favorably changed the flow in the diffuser, allowing it to be more symmetrical about the longitudinal centerline.

The peculiar flow behavior in the IRT diffuser prompted the numerical simulation study which began with the PEPSIG code. This code was used to simulate diffuser flow over a range of airspeeds. The vertical velocity profiles in Fig. 24 indicates the manner in which PEPSIG predicts the profile changes as the flow progresses from the test
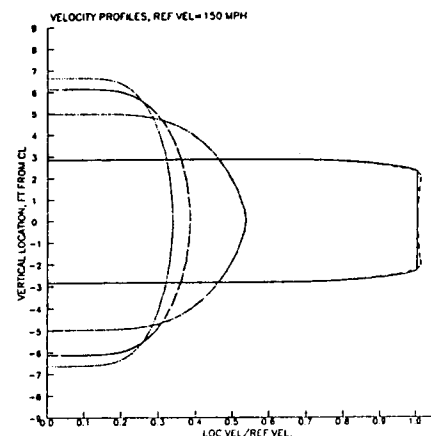

Fig. 24 Vertical Velocity Profiles at Various Longitudinal Locations in Diffuser as Predicted by PEPSIG

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section and down through the diffuser. The vertical profiles are not plotted as a function of distance from the floor, but rather as the distance from the tunnel centerline since the vertical dimension of the diffuser is constantly changing along its length. The profiles remain symmetric about the centerline throughout the diffuser and progress from a uniform, relatively flat shape in the test section to a nonuniform, parabolic shape midway down the diffuser, then back to a more relatively flat shape near the end of the diffuser. The horizontal profiles predicted are much the same and both horizontal and vertical profiles show little variation with speed.

Figs. 25 and 26 compare PEPSIG horizontal velocity profiles with measured velocity profiles at the entrance and exit of the diffuser, respectively. The profiles are very similar at the diffuser entrance with the exception of the small disturbance measured near the right-hand wall which is caused by the facility Pitot-static tube. However, the profiles are very much different at the diffuser exit. Apparently, the PEPSIG code overpredicts the amount of turbulent mixing or viscous dissipation which occurs. Further evidence of this can be seen when the PEPSIG contour plot of Fig. 27 is compared with the measured contour plot of Fig. 28. The PEPSIG code also does not predict the double-parabola velocity profiles that exist in the tunnel as shown in Fig. 17. However, the code does predict a small amount of separation in each of the four corners of the tunnel's cross section as is reflected in the contour plot of Fig. 27.
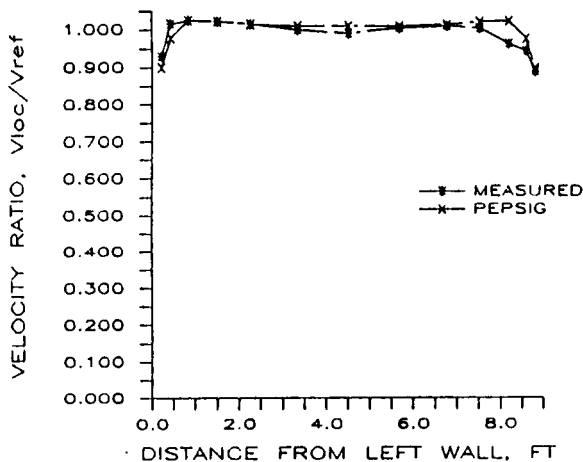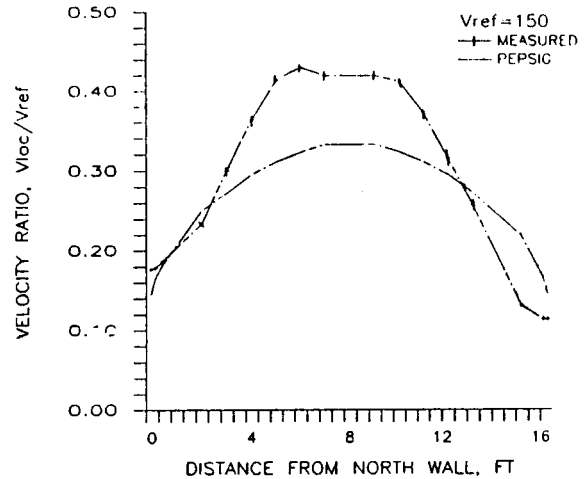

Fig. 26 Comparison of Horizontal Velocity Profiles at Diffuser Exit, PEPSIG and Measured

Fig. 27 Velocity Contours at Diffuser Exit as Predicted By PEPSIG, Reference Velocity = 150 mph
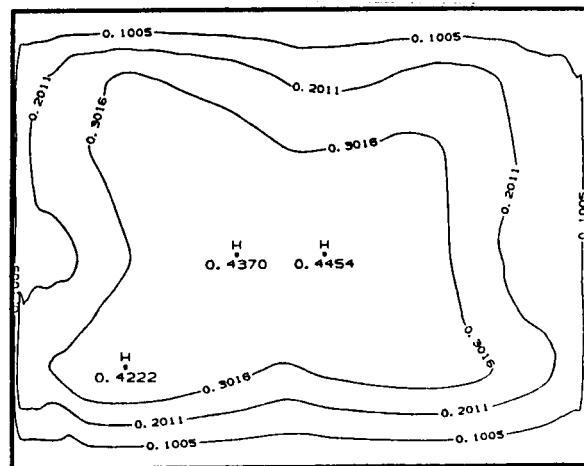

Fig. 25 Comparison of Horizontal Velocity Profiles at Diffuser Entrance, PEPSIG and Measured

Fig. 28 Measured Velocity Contours at Diffuser Exit, Reference Velocity = 150 mph

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CONCLUSIONS

The aerodynamic measurements made in the diffuser of the IRT show that obstructions upstream in the tunnel do indeed affect the flow in this part of the tunnel. The facility Pitot-static tube itself has both an aerodynamic and thermodynamic signature which can be traced far downstream, while the removal of the spray bar control valves and associated hardware from the settling chamber dramatically changed the velocity profile in the exit of the diffuser.

Furthermore, the measurements indicate a degree of complexity heretofore unanticipated. The temperature uniformity suggests that significant mixing is occuring; however, the velocity profiles indicate that a strong core flow remains intact throughout the diffuser.

The double parabolic shapes of the horizontal velocity profiles discovered both high and low in the diffuser exit were unexpected. The source of this behavior is unknown, however, it does seem to have the effect of energizing the corners which helps retard the flow separation which is anticipated in these areas by the PEPSIG code.

PEPSIG was chosen as the initial simulation code not only because it does not require large amounts of cpu time, but because it also has the capability to simulate the effect of vortex generators. Unfortunately, its prediction of the IRT's flow characteristics is so different than what actually occurs that it was determined that little could be gained by investigating their effect in the diffuser's geometry. The use of the more rigorous PARC code will help determine whether or not PEPSIG is overlooking an important factor in its assumptions and hopefully will add more insight to the IRT's flow characteristics.

Finally, more measurements in the tunnel will add more pieces to the puzzle.

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16. Abstract

The flow in the diffuser section of the Icing Research Wind Tunnel at NASA Lewis Research Center is investigated
using both tunnel calibration measurements and numerical simulation techniques. Local pressure and temperature
measurements are made to establish velocity and temperature profiles in the diffuser of the tunnel. These profiles
are compared with similar measurements made prior to renovating the equipment which generates the tunnel's
icing cloud. This comparison indicates the manner in which this change affected the flow. The measured data
were also compared with a numerical simulation of the flow to help understand how such changes may favorably
alter the tunnel flow.

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